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Performance Estimation of a Louver Dust Collector Attached to the Bottom of a Subway Train Running in a Tunnel

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ABSTRACT

In underground tunnels, friction between the wheels and rails of subway trains creates particles, which are spread by the wind generated when trains pass by. A louver dust collector was attached to the bottom of a T-car of Seoul Subway Line 5 train in an effort to remove PM_{10} inside tunnels, and obtain data when it was in actual operation. It made several round trips during which differential pressure of the louver dust collector was measured in relation to train speed. By comparing and verifying the differential pressure estimated by simulation and that actually measured, it was possible to estimate average flow of air that went into the louver dust collector. Furthermore, by comparing and verifying the measurement results on collection efficiency of a lab-scale louver dust collector in a wind tunnel, along with the results of numerical analysis, it was possible to estimate the collection efficiency in relation to subway train speed. As a result, it was confirmed that higher running speeds of subway trains increased the flow of air going into the louver dust collector and subsequently decreased the particle size corresponding to 50% collection efficiency. In other words, the cut-off size was estimated to be 9.7 µm at the lowest speed of 5 km h^{-1}, and 4.9 µm at the top speed of 65 km h^{-1}, in normal speed range for the Seoul Subway Line 5 trains.

Keywords: Underground tunnel; Subway train; Louver dust collector; Collection efficiency.

INTRODUCTION

Subway trains provide a means of public transportation that is widely used by many people around the world. For example, in Seoul, the capital city of the Republic of Korea, there are 13 subway lines currently in operation and about 7.5 million people use them every day. Due to friction between train wheels and rails, as well as between brake disks and shoes, PM_{10} consisting of metallic particles (Fe being a major component, but also Cr, Mn, Cu, and Zn) are generated in underground tunnels (Kang *et al.*, 2008; Raut *et al.*, 2009; Salma *et al.*, 2009; Jung *et al.*, 2010, 2012). The generated PM_{10} has a great influence on air quality inside the subway train (Cheng *et al.*, 2012), and spreads to the platform due to the wind created when trains pass (Park *et al.*, 2014). The concentrations of PM_{10} and $PM_{2.5}$ of the dusts that are spread to the platform become gradually higher as time goes by (Kim *et al.*, 2008; Ma *et al.*, 2015). Because citizens intending to use a subway train linger in the platform, this exposure to PM_{10} could cause respiratory disease and asthma and have a significant impact on children and senior citizens in particular (Curtis *et al.*, 2006). The importance of air quality management in underground tunnels is increasing, and therefore many studies on fine particles (PM_{10} and $PM_{2.5}$) in underground tunnels have been conducted in major cities like Beijing (Fan *et al.*, 2016), Helsinki (Aarnio *et al.*, 2005), Paris (Raut *et al.*, 2009), Seoul (Park and Ha, 2008), Stockholm (Johansson and Johansson, 2003), and Taipei (Cheng and Lin, 2010).

There was an attempt to increase the efficiency of removing PM_{10} and $PM_{2.5}$ that escaped through vents to the outside by attaching a magnetic filter to a subway ventilation system (Son *et al.*, 2014). By establishing a bundle-type electric filter in the Mechanical Ventilation and Air-Conditioning (MVAC) system in the subway, the amount of particles that went through increased and at the same time the efficiency of fine particle removal was raised (Li and Jo, 2010). By installing an electrostatic precipitator in Parisian subway station, the amount of particles that was actually collected as time passed could be identified (Tokarek and Bernis, 2006). Ventilation efficiency was improved by applying an air curtain and by reducing the concentration

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of pollutant dust and particles in the tunnel (Ryu *et al.*, 2012). Furthermore, there was a study on the behavior of particles at the bottom of a subway train in operation (Lee *et al.*, 2016).

Although the research continues on PM_{10} removal in underground tunnels, it can be said that there have been few studies on removing PM_{10} by directly attaching a dust collector to a running train while allowing it to continue to run. Due to broad size range of particles in subway tunnels, a dust removing system can be composed of two parts, e.g., one part for collecting coarse particles and the other part for removing finer particles. Jung *et al.* (2012) sampled particles (< 25 µm) at some subway stations in Seoul and showed that airborne particles were mostly smaller than 10 µm. Therefore, this research aims to estimate collection efficiency for PM_{10}, especially coarse particles, by attaching a louver dust collector to the bottom of a subway train. Because the louver dust collector is simple in appearance, creates low pressure drop, and uses inertia of particles to gather dust into the collector, it is considered efficient to remove dust passing very quickly into collectors in the space under a subway train running at high speeds. In this study, a louver dust collector is attached to the bottom of the T-car of a Seoul Subway Line 5 train, and the differential pressure is measured during the running of the subway train. This research also compares and verifies the differential-pressure values estimated by computational fluid dynamics (CFD) simulation and the measured values, in order to estimate the average flow rate of air at the entrance of the louver dust collector. Using a method of numerical analysis established by comparing and verifying the results of collection efficiency of a lab-scale louver dust collector, this study is intended to determine the collection efficiency in relation to the average flow rate of air entering the louver dust collector attached to the bottom of the subway train running in a tunnel at various speeds.

NUMERICAL

In order to analyze the flow of air that goes around a subway train using CFD, a three-dimensional model of a subway train was established first. For this study, the model chosen was the Seoul Subway Line 5 train, to which a louver dust collector was attached and used to measure the differential pressure. As shown Fig. 1, the Seoul Subway Line 5 train had eight passenger cars in total and was symmetric from the left to the right. Cars 1 and 8 were TC-Cars, Cars 2 and 7 were M1-Cars, Cars 3 and 6 were M2-Cars, and Cars 4 and 5 were T-Cars. A three-dimensional view of this train can be found elsewhere (Lee *et al.*, 2016). As illustrated in Fig. 2, the train was 3.2 m in width, 4.25 m in height, and 160 m in length, and the underground tunnel where the train passed was also modeled in accordance with the actual tunnel specifications, that is, 8.6 m in width and 6 m in height. The entire tunnel length was set at 960 m by considering 400-m-long spaces ahead and behind the 160-m-long subway train.

Fig. 3(a) shows the louver dust collector attached to the bottom of a subway train. It had one layer consisting of eight louver blades and one dust container, with a total of four independent layers. In addition, Fig. 3(b) shows the cross-section of one layer of this louver dust collector and detailed dimensions for the louver blades and the dust container.

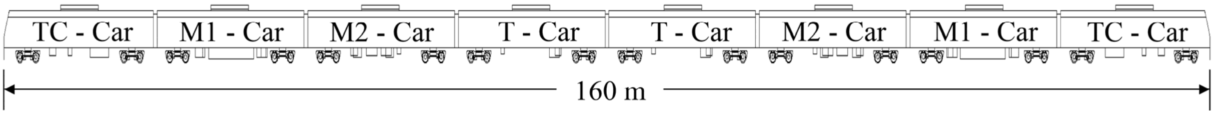

Fig. 1. Shape of an eight-passenger-car subway train.

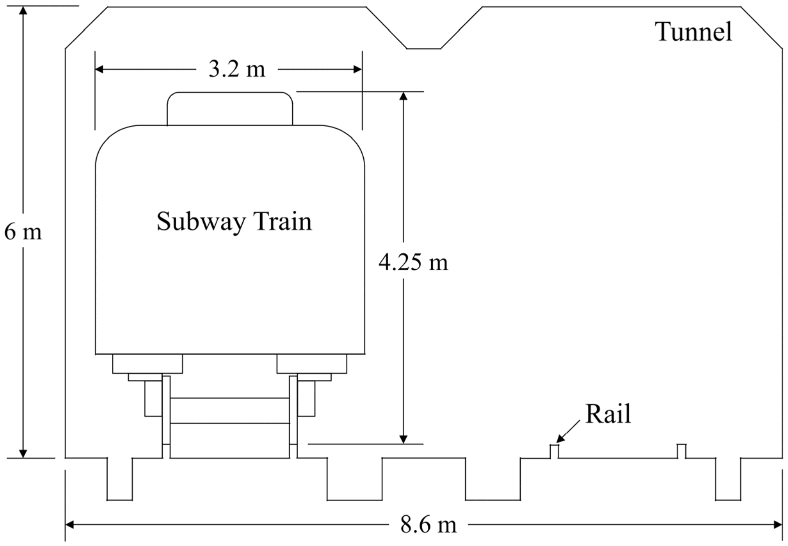

Fig. 2. Cross section of tunnel and subway train.

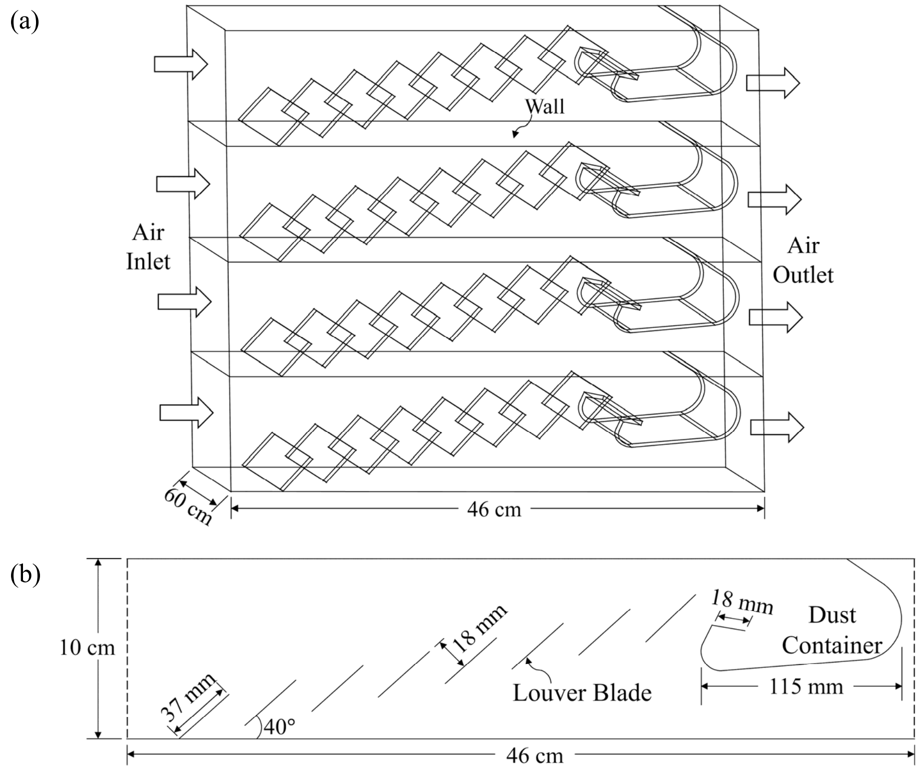

Fig. 3. Shape of louver dust collector: (a) Three-dimensional view (b) Side view and detailed dimensions.

For flow analysis, approximately 7 million grid cells were constituted around a subway train, including the bottom, while about 12 million grid cells were configured for the tunnel. As the bottom of a subway train was complex in shape, tetrahedral grids were used for it while hexahedral grids were used for the tunnel. Compared with a subway train, the louver dust collector was very small and complex in shape as depicted in Fig. 3, making it difficult to configure grids at the same level. Therefore, in this study, we came up with an orifice shape that formed the same differential pressure as the louver dust collector on the bottom of a subway train as illustrated in Fig. 4, through a numerical parametric study performed by varying the orifice size. The orifice shape was modeled at the bottom of the 4th T-Car as in the same place where the louver dust collector was actually installed for field experiments.

To analyze the air flow around a train running in a tunnel, a commercial CFD code, ANSYS FLUENT *Release 16.1*, was used. The standard k-ε turbulence model based on the RANS equation was used (Kim and Kim, 2007; Cao *et al.*, 2012). The flow status options were set to steady, incompressible, no-slip wall, and three-dimensional. In order to simulate a subway train running in an underground tunnel, the subway train was set stationary with its wheels and brake disks rotating while the tunnel wall was set to move from left to right at the same velocity as the train speed. The velocity inlet boundary condition was set for the tunnel entrance while the pressure outlet boundary condition was set for the tunnel exit. For the solution method, the SIMPLE scheme was set for pressure-velocity coupling, and the second order upwind discretization scheme was chosen to discretize the governing equations (Kim and Kim, 2007). The convergence criteria were set at 10^{-3} for the continuity and momentum equations and 10^{-6} for the energy equation. A more detailed description of the numerical scheme employed in this study can be found in our previous publication (Lee *et al.*, 2016).

To estimate the collection efficiency of the louver dust collector through numerical analysis, a lab-scale louver dust collector was also manufactured. It should be noted that the lab-scale louver dust collector had two layers as illustrated in Fig. 5 and the width of the lab-scale louver dust collector was 0.3 m, that is, half of the width of the actual louver dust collector attached to the subway train bottom. The calculation domain for simulating the collection efficiency of the lab-scale louver dust collector was the same as the schematic shown in Fig. 3(b) but with two layers. For flow analysis, approximately 0.25 million triangular grid cells were configured in total while about 10000 triangular grid cells were configured inside the dust container. The flow was assumed to be two-dimensional, steady, incompressible, and turbulent. The k-ω turbulence model was applied to the RANS equation to simulate the flow in the louver dust collector (Musgrove *et al.*, 2009, 2013). The velocity inlet boundary condition was set for the inlet of the louver dust collector, and the pressure outlet boundary condition for the outlet. For particle injection, the DPM function embedded in the FLUENT was used. Particles were assumed to be reflected at the louver blade surfaces, and trapped only at the surface of the dust container. After injecting 1000 particles, at a constant spacing between neighboring particles, from a vertical imaginary line at the entrance, this study

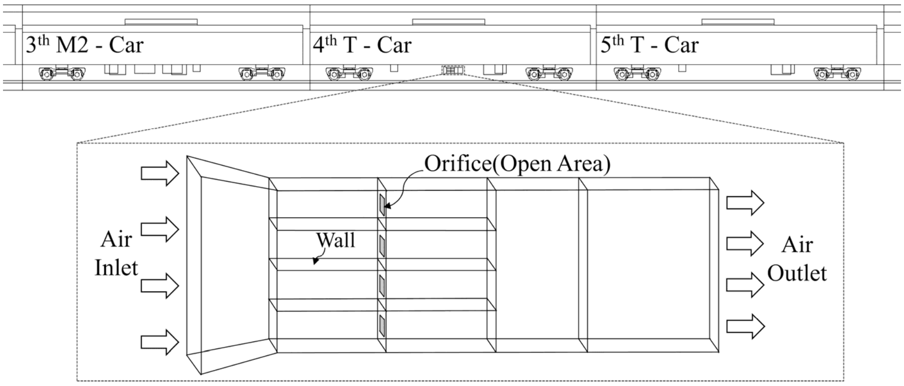

Fig. 4. An imaginary dust collector, having four orifices, attached to the bottom of a subway train.

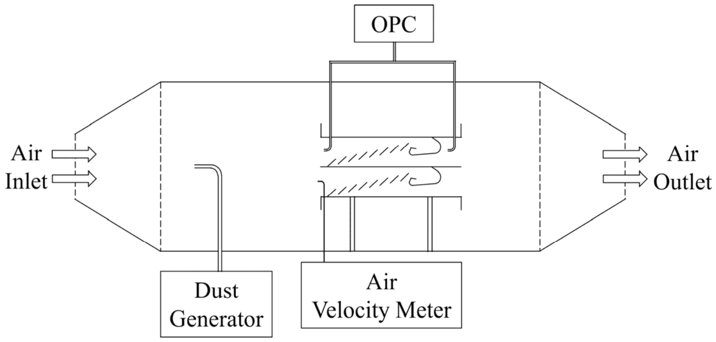

Fig. 5. Schematic of the experimental setup with a lab-scale wind tunnel.

calculated the number of particles trapped in the dust container to determine the collection efficiency of the louver dust collector. The particles were assumed to be spherical. The particle density was set at 3 g cm^{-3} for simulating the collection efficiency of the lab-scale louver dust collector, by considering the JIS Z8901 Class 8 test particles used for lab-scale experiments. The Cunningham slip corrector factor was applied for the Stokes' law. The Brownian motion of particles was considered. With regard to the convergence criteria, 10^{-3} was set for all variables.

By using the numerical analysis method established by verification of the results of the experiment with a lab-scale wind tunnel, the collection efficiency of the actual louver dust collector, which was attached to the bottom of a subway train, was estimated based on the amount of flow that went into the louver dust collector and the particle density of 7.87 g cm^{-3}, i.e., the density of iron contained in subway-tunnel particles. According to Jung *et al.* (2012), the shapes of the particles sampled at some subway stations in Seoul were various. However, in the present numerical approach, the particles were assumed to be spherical. It should be noted that the mean airflow velocity at the inlet of the dust collector with orifices was first obtained from the three-dimensional full-scale simulation of the airflow around the eight-passenger-car subway train as illustrated in Fig. 4, and then this mean airflow velocity was used as the velocity inlet boundary condition for the collection-efficiency simulation using a two-dimensional calculation domain of four-layered louver dust collector, of which layer-cross-section is shown in Fig. 3(b).

EXPERIMENTAL

A lab-scale experiment was conducted for the purpose of validating the numerical approach that was used to predict the collection efficiency of louver dust collectors. Fig. 5 shows an experimental setup for measuring the collection efficiency of the lab-scale louver dust collector in a wind tunnel. The lab-scale louver dust collector had two layers as depicted in Fig. 5, and each layer was composed of eight louver blades and one dust container as shown in Fig. 3(b). The width of the lab-scale louver dust collector was 0.3 m. JIS Z8901 Class 8 test particles (ρ_p = 3 g cm^{-3}) were aerosolized using a solid aerosol generator (SAG 410, TOPAS, Dresden, Saxony, Germany), and the aerosol was injected into the wind tunnel in the direction opposite to the airflow direction. The air flow rate at the entrance of the lab-scale louver dust collector was measured using an air velocity meter (Model 9535, TSI, Shoreview, MN, USA). An optical particle counter (OPC, Model 1.109, GRIMM, Ainring, Bayern, Germany) was used to measure the particle size distributions upstream and downstream of the lab-scale louver dust collector by manually connecting the sampling line to upstream probe or downstream probe.

On the other hand, a field test was performed by attaching a louver dust collector, having four layers as illustrated in Fig. 3(a), to the bottom of a subway train, in order to measure the pressure drop across the louver dust collector in relation to train speed during real operation. Fig. 6 shows a photo of the louver dust collector attached to the bottom of the fourth T-car of the Seoul Subway Line 5 train with the cooperation of the Seoul Metropolitan Rapid Transit Corporation. A guide vane with an entrance area of 0.48 m^2 (0.96 m × 0.5 m), which was larger than the entrance area of the louver dust collector, and width of 0.2 m, was installed at the entrance of the louver dust collector in order to guide the flow into the collector. A manometer (MP 210, KIMO Instruments, Montpon, Dordogne, France) was used to measure the pressure drop across the louver dust collector. The train made several round trips with the experimental set up in place. Because the collector was installed to face in only one direction, data were gathered only when the subway train moved in the direction helping the air to enter the inlet of the louver dust collector. By matching the subway train speed and the differential pressure based on the time of measurement, it was possible to measure the differential pressure according to the speed of the subway train.

RESULTS AND DISCUSSION

The results of lab-scale louver dust collector experiment on collection efficiency were compared with the results of numerical analysis, and then verified. Fig. 7 shows the dust collection efficiency according to particle size, when the airflow velocity at the inlet of the lab-scale louver dust collector was 2.98 m s^{-1} (which was the airflow velocity at the inlet of the actual louver dust collector at the train speed of about 38 km h^{-1} as shown in Fig. 10). For the simulation of the lab-scale louver dust collector, particles were assumed to be spherical with the density of 3 g cm^{-3}, that is, the density of the JIS Z8901 Class 8 test particles used for the lab-scale experiments. As compared in Fig. 7, the numerical results showed a good agreement with the experimental data, for the lab-scale louver dust collector. Especially, the cut-off size, that is, the particle size at 50% collection efficiency, agreed very well with the experimentally determined cut-off size with the error of less than 6%. Even through the collection efficiency curve determined by the present numerical approach was stiffer than that obtained by the experiments, the present numerical approach was considered to correctly predict the collection efficiency of the louver dust collectors.

A numerical parametric study was performed to find an appropriate size of the orifices showing the same pressure drop as the actual louver dust collector attached to the bottom of the subway train. A full-scale three-dimensional simulation was repeatedly conducted by varying the orifice size in the calculation domain shown in Fig. 4, at some selected train speeds. Fig. 8 shows an exemplary plot of velocity vectors around the eight-passenger-car subway train with a magnified figure of the four-layered collector

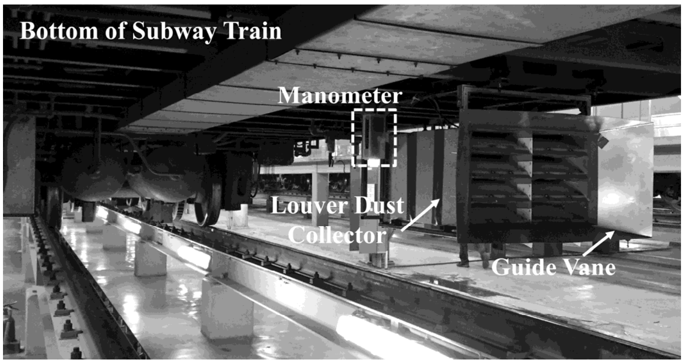

Fig. 6. Photo of lover dust collector, differential pressure gauge, and guide vanes attached to the bottom of a subway train.

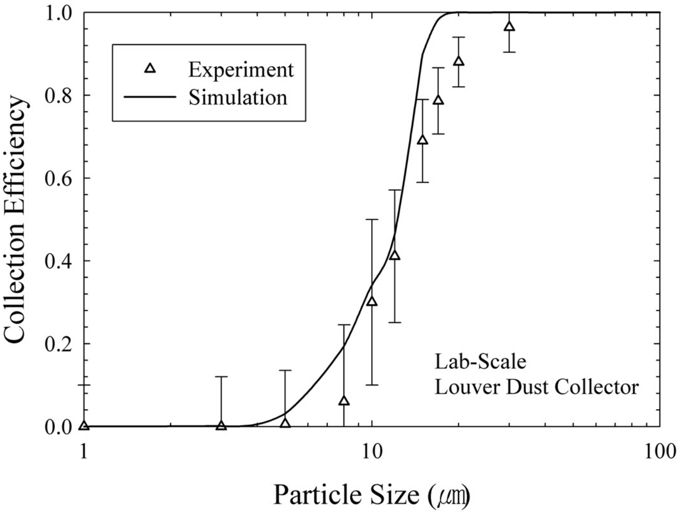

Fig. 7. Comparison of collection efficiency between experimental data and numerical results.

with four orifices. Once the flow field was obtained, the mean pressure drop across the dust collector was estimated and compared with the experimental data. As a result of the numerical parametric study, the orifice size was determined as 340.0 mm × 47.7 mm.

Fig. 9 illustrates the results of dividing subway train speed into seven speed-steps, and comparing the differential pressure according to each of those steps, between actual measurement and numerical analysis. In both the measured and the numerical analysis results, it was found that the differential pressure increased as the inflow increased when a subway train went faster. Given the margin of error for the measured values, it was found that the measured results and the simulated results were very consistent, meaning that the orifice size was properly determined to represent the pressure drop across the actual louver dust collector.

In case of an incompressible and non-viscous fluid like air under these conditions, pressure and velocity have a correlation according to Bernoulli's principle. Therefore, it was possible to estimate the speed and flow of air entering the louver dust collector using numerical analysis through verification of the differential pressure on the dust collector. Fig. 10 describes the average velocity of air flowing into the actual louver dust collector, predicted by the numerical simulation with the assumed orifices, according to subway train speed. It was confirmed that the average inflow air velocity linearly increased as the train speed increased. Within the normal range of the subway train speed, i.e., 5–65 km h^{-1}, the average velocity of air at the inlet of the actual louver dust collector was estimated to range between approximately 0.4 and 5 m s^{-1}. By considering the range of the inflow air velocity at the inlet of the louver dust collector and the cross-sectional area of the louver dust collector, i.e., 0.24 m^2 (0.6 m × 0.4 m), the flow rate of air through the louver dust collector was estimated to be about 6600–72000 L min^{-1}. In other words, the amount of air that could be filtered by this louver dust collector was anticipated to be approximately 0.4–4.3 million liters per hour.

Through the numerical analysis method established for the lab-scale louver dust collector experiment, this study aimed to show the collection efficiency of the actual louver dust collector installed at the subway train bottom, in

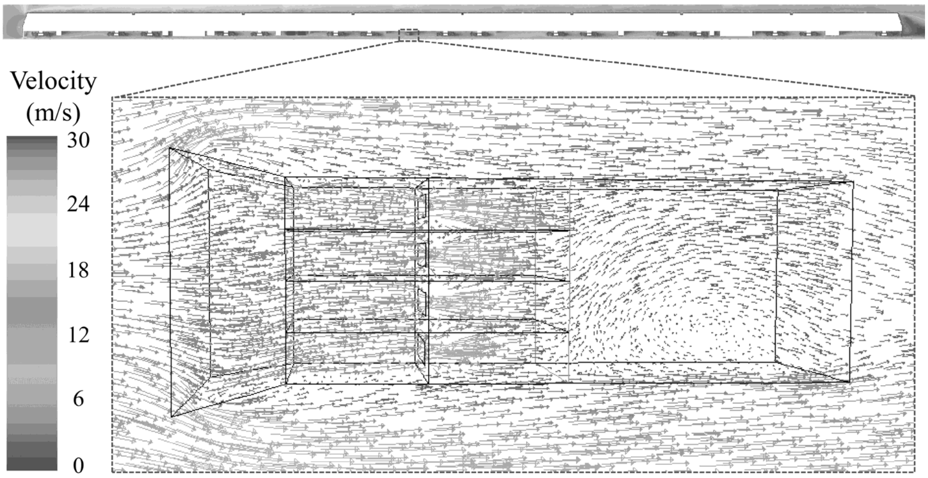

Fig. 8. Velocity vectors of the airflow around the eight-passenger-car subway train.

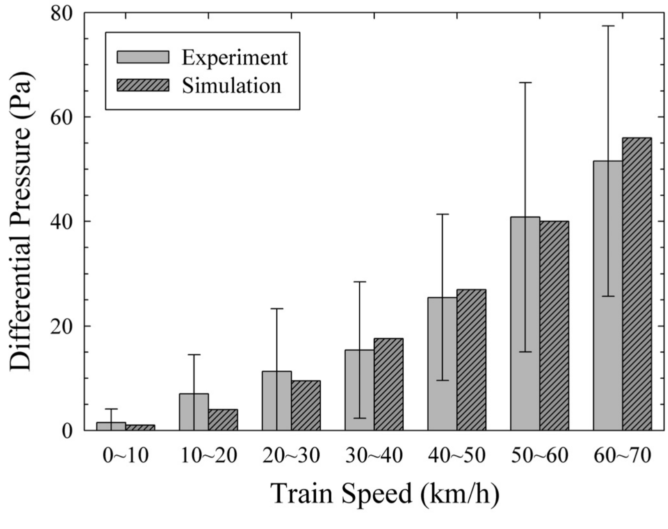

Fig. 9. Comparison of pressure drop across the louver dust collector between experimental data and numerical results.

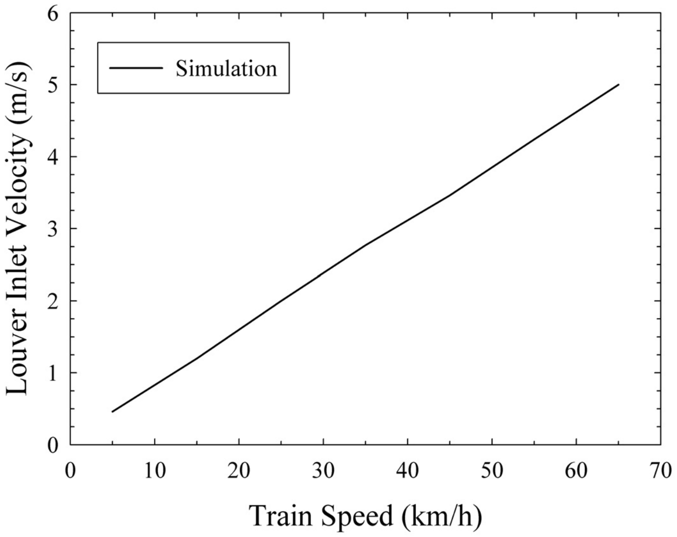

Fig. 10. Mean velocity of air flow at the entrance of the louver dust collector according to the subway train speed.

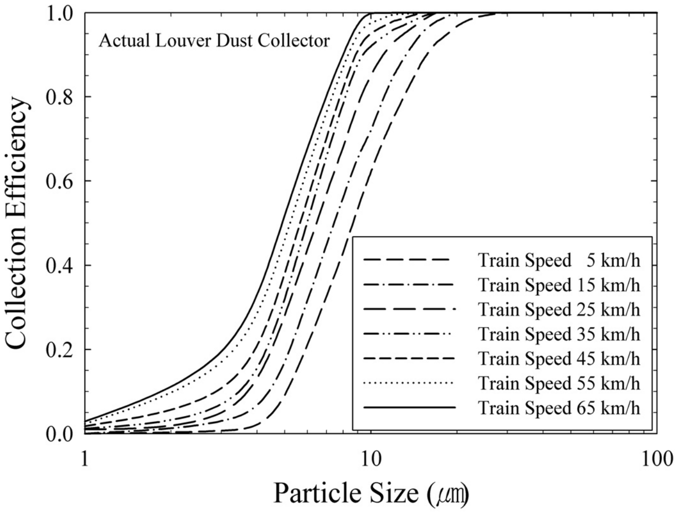

Fig. 11. Collection efficiency of the louver dust collector attached to the bottom of a subway train at various train speeds.

accordance with the speed of a subway train. Because the louver dust collector attached to the bottom of a subway train had four layers, a two-dimensional domain displayed in Fig. 3(b) was modeled to have four layers. The average inflow velocity of air at the entrance of the louver dust collector according to subway train speed described in Fig. 10 was used as an inlet speed to conduct a parametric study to predict the collection efficiency of the actual louver dust collector attached to the subway train bottom. Fig. 11 shows the collection efficiency according to subway train speed, within the actual speed range of a normally operating Seoul Subway Line 5 train. Because iron is known to be the most common material contained in the particles observed in subway tunnels (Kang *et al.*, 2008; Raut *et al.*, 2009; Salma *et al.*, 2009; Jung *et al.*, 2010, 2012), spherical particles having the density of iron (ρ_p = 7.87 g cm^{-3}) were assumed. When it came to the cut-off size for each speed-step, 9.7, 7.5, 6.7, 6.2, 5.8, 5.3, and 4.9 µm were estimated in order from the lowest speed-step (5 km h^{-1}) to the highest (65 km h^{-1}). It was therefore confirmed that the cut-off size decreased as the train speed went up, and that the highest collection efficiency was estimated to occur at the speed of 65 km h^{-1}, normally the highest speed of the Seoul Subway Line 5 train. By its nature, the louver dust collector uses the inertia of particles to collect them. When a subway train runs at a high speed, its collection efficiency is high, and predictably, when a train runs slowly, its collection efficiency becomes relatively low. Accordingly, the findings of this study also confirmed that as a subway train speed increased, the flow entering the louver dust collector increased and so did the collection efficiency.

CONCLUSIONS

This research was intended to estimate the efficiency to remove PM$_{10}$, especially coarse particles, inside subway tunnels from use of a louver dust collector attached to the bottom of a subway train. Through numerical analysis, it was possible to estimate the average flow rate of air going into the louver dust collector and predict the collection efficiency of the louver dust collector according to the subway train speed. Within the normal speed range for a Seoul Subway Line 5 train, that is, 5–65 km h^{-1}, the cut-off size of the louver dust collector developed in this study was estimated to range from approximately 5 to 10 µm. With this study's field experimental set-up, the louver dust collector only collected dust in one direction. Therefore, if the collector were modified to collect dust in both directions possible for a subway train, the louver dust collector considered in this study would be expected to be helpful to effectively reduce the amount of coarse particles in the subway tunnels, especially particles larger than approximately 5 µm. In future studies, it is needed to develop a dust collector like an electrostatic precipitator, which can remove finer particles, and combine it with the louver dust collector.

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